Limiting excitation energy in the reaction Si+Si

Griffioen, KA; Meijer, RJ; Box, PF; Decowski, P; Van Nieuwenhuizen, GJ; Kamermans, R; Wilschut, HW; Giorni, A; Morand, C; Demeyer, A

Published in:
Physics Letters B

DOI:
10.1016/0370-2693(90)90454-E

LIMITING EXCITATION ENERGY IN THE REACTION Si+Si

K.A. GRIFFIOEN [a,b], R.J. MEIJER [b,1], P.F. BOX [b], P. DECOWSKI [b,2],
G.J. VAN NIEUWENHUIZEN [b], R. KAMERMANS [b], H.W. WILSCHUT [c], A. GIORNI [d],
C. MORAND [d], A. DEMEYER [e] and D. GUINET [e]

[a] *Department of Physics, University of Pennsylvania, Philadelphia, PA 19104, USA*
[b] *Robert J. van de Graaff Laboratorium, Rijksuniversiteit Utrecht, Princetonplein 5, NL-3508 TA Utrecht, The Netherlands*
[c] *Kernfysisch Versneller Instituut, Zernikelaan 25, NL-9747 AA Groningen, The Netherlands*
[d] *Institut des Sciences Nucléaires, Avenue des Martyrs 53, F-38026 Grenoble Cedex, France*
[e] *Institut de Physique Nucléaire, Université Claude Bernard,
43 Boulevard du 11 Novembre 1918, F-69622 Villeurbanne Cedex, France*

Received 27 September 1989

We have measured energy and angular distributions of protons and α-particles in coincidence with evaporation residues for the reaction Si+Si at beam energies 12.4, 19.7, and 30.0 MeV/N. The reconstructed excitation energies of composite systems decaying into evaporation residues saturate near 3 MeV/N with increasing beam energy. This is consistent with a limiting excitation energy between 4 and 5 MeV/N above which sequential evaporation does not occur.

Although nucleus–nucleus collisions provide a testing ground in the laboratory for nuclear matter at high temperatures, the interpretation of the observations depends on a good understanding of the reaction dynamics. Ideally one would like to decouple the dynamics of a central collision from the properties of the hot nuclear mass that forms in the process. One way to approach this goal experimentally is to detect evaporation residues, the remnants of moderately hot nuclei, in coincidence with light particles (protons and α-particles), the products of decay. For the reaction Si+Si we pose two questions: (1) what is the initial excitation energy of the composite system formed by two incompletely fusing heavy ions and (2) what is the maximum excitation energy that such a system can sustain and still decay into an evaporation residue?

We have bombarded natural Si targets with ^{28}Si beams produced by the cyclotrons at KVI (12.4 MeV/N) and SARA (19.7 and 30 MeV/N). Using an ionization chamber-Si detector combination at small angles to trigger on evaporation residues, we looked at protons and α-particles entering any of a number of detector telescopes which covered angles from 5° to 170° both in- and out-of-plane. For the 12.4 MeV/N runs at KVI we made use of standard Si-detector telescopes as well as Si–Si–CsI combinations [1], whereas at 19.7 and 30 MeV/N we used the Utrecht multidetector array [2] which consists of Si–CsI telescopes. A full discussion of this experiment appears elsewhere [3–5]. We selected evaporation residues by setting gates on the charge and energy of the detected heavy ions. At all three beam energies the coincidence data correspond to charges $Z \geqslant 15$, where contributions from peripheral processes are negligible. With these gates we have generated the proton and α-particle energy spectra $d^3\sigma/d\Omega_{HI}d\Omega_{LP}dE_{LP}$ for each light-particle angle. These data were then normalized to the simultaneously measured and identically gated inclusive cross sections $d\sigma/d\Omega_{HI}$ in order to obtain the differential multiplicities $d^2M/d\Omega_{LP}dE_{LP}$.

We have described our data using a coincidence moving source parametrization [6]. For the symmetric Si+Si system, the model contains equivalent pieces due to projectile and target promptly emitted

[1] Present address: GSI, D-6100 Darmstadt, FRG.
[2] On leave from the University of Warsaw, PL-00-681 Warsaw, Poland.

particles (PEP's) centered near $v = v_{\mathrm{beam}}$ and $v = 0$ respectively, and a third source at the center-of-mass (CM) velocity which describes evaporation from a composite system. Fig. 1 shows representative coincidence data at 19.7 MeV/N. A single set of parameters fits all in- and out-of-plane angles simultaneously. Neither PEP nor CM contribution alone adequately describes the data. The coincidence moving source parametrization accounts very well for the kinematic effects which make the cross section for angles opposite the ionization chamber considerably larger than for the equivalent angles on the same side of the beam. Integration of the parametrized differential multiplicities over solid angle and energy gives p and α multiplicities and average energies for the CM component (table 1). From these we can deduce the average initial properties of the hot composite system [7]. Its average mass is given by

$$\overline{A_{\mathrm{CS}}} = \sum_i 2M_i Z_i + 2\overline{Z_{\mathrm{ER}}}, \qquad (1)$$

where M_i is the multiplicity of particle type i, Z_i is its charge, and $\overline{Z_{\mathrm{ER}}}$ is the average charge of the residue. (For these relatively light nuclei the most probable mass number runs close to $A = 2Z$.) The average excitation energy of the composite system is simply

$$\overline{E^*} = \sum_i M_i(\overline{E_i} + \Delta_i) + \overline{E_{\mathrm{ER}}} + \overline{E_\gamma} + \overline{\Delta_{\mathrm{ER}}} - \overline{\Delta_{\mathrm{CS}}}, \qquad (2)$$

where $\overline{E_i}$ is the average energy of the ith particle type, Δ_i is the corresponding mass excess, $\overline{E_{\mathrm{ER}}}$ is the aver-

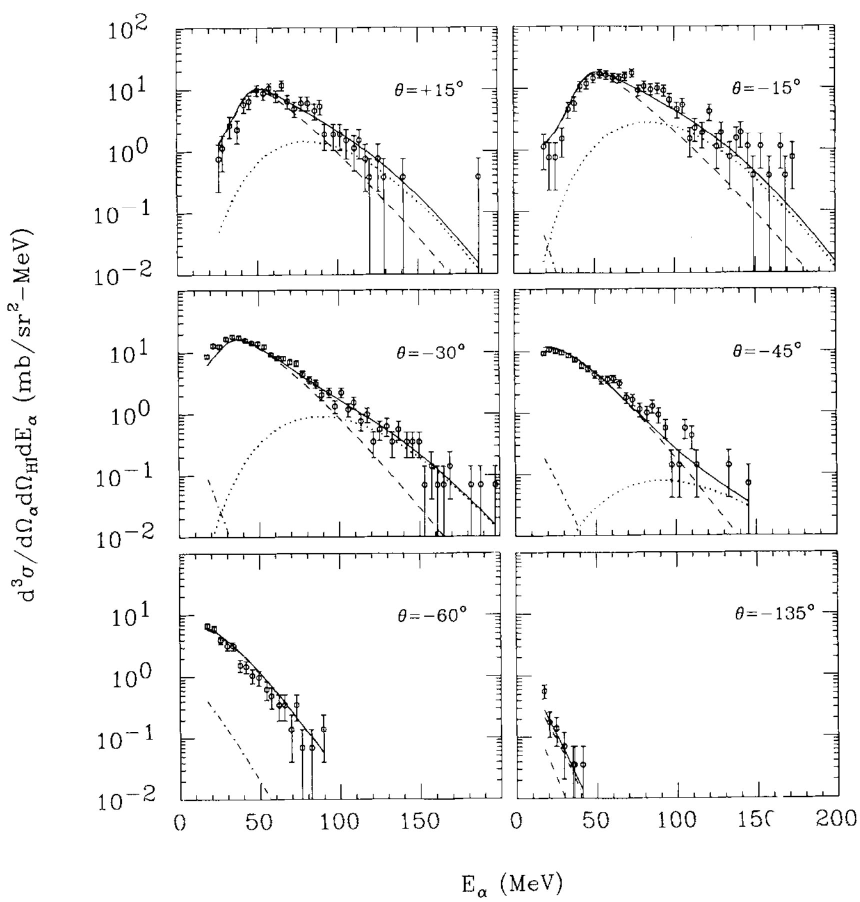

Fig. 1. α-particle energy spectra at 19.7 MeV/N gated on residues ($Z \geqslant 15$) for selected in-plane angles. Positive θ refers to the same side of the beam as the heavy-ion counter. The solid curve is the best fit to the coincidence moving source parametrization. The dashed, dotted, and dot-dashed curves correspond to the CM, forward PEP, and backward PEP contributions, respectively.

Table 1
Average properties of the CM component in the reaction Si+Si. Numbers in parentheses are statistical errors corresponding to the last digit. We estimate the [unmeasured] neutron particle emission assuming that $M_n = M_p$ and that the energy distribution of neutrons is identical to that of protons with the Coulomb barrier removed.

E_{beam} (MeV/N)	E_{cm} (MeV)	M_p	M_α	$\bar{E}_p$ (MeV)	$\bar{E}_n$ (MeV)	$\bar{E}_\alpha$ (MeV)	$\overline{Z_{ER}}$	$\overline{A_{CS}}$	$\overline{E^*}$ (MeV)	$\overline{E^*}/\overline{A_{CS}}$ (MeV/N)
12.4	174	3.9(6)	2.1(3)	7.78	7.27	14.74	19	54(4)	185(20)	3.4(4)
19.7	276	2.2(3)	1.1(2)	10.67	9.64	18.24	16.5	42(4)	118(20)	2.8(5)
30.0	420	2.0(3)	0.8(1)	11.54	10.53	22.27	15.7	39(4)	112(20)	2.9(6)

age kinetic energy of the residue in the CM frame, $\overline{E_\gamma}$ is the (unobserved) energy carried off by γ-radiation, and Δ_{ER} and Δ_{CS} are the average mass excesses for the residue and the composite system, respectively. To first order, the mass and energy carried off by d, t, ^{3}He, etc. (about 10% of the p plus α yield) do not affect the extracted excitation energy per nucleon. We estimated the quantity $\overline{E_{ER}} + \overline{E_\gamma}$ to be 10 MeV [7]. Clearly from table 1, $\overline{E^*}/\overline{A_{CS}}$ saturates with beam energy at roughly 3 MeV/N. Ref. [7] indicates that the errors in reconstructing excitation energy using eq. (2) are on the order of 10 MeV.

Other observations on Si+Si are as follows: (1) The total evaporation residue cross sections at 12.4, 19.7, and 30 MeV/N are 500, 270, and 18 mb, respectively, with 20% error bars. The data [8] for Si+Si measured in the range 5–20 MeV/N (including our points at 12.4 and 19.7 MeV/N) fall along the line $\sigma(\text{mb}) = (74900 \pm 2100)/E_{cm}(\text{MeV})$ with χ^2 per degree of freedom of 0.8. The systematic trend implies that $\sigma = 178$ mb at 30 MeV/N, which is a factor of ten larger than our measured value. Therefore, at our highest energy the residue cross section is disappearing into competing reaction channels. (2) The centroid of the distribution of residues moves toward lower Z with increasing beam energy, but remains fixed between 20 and 30 MeV/N. This suggests a limiting excitation energy for systems that produce these residues. (3) If incomplete fusion occurs by emission of particles at target and projectile velocities in the symmetric system Si+Si, then the excitation energy per nucleon should be 7.5 MeV/N for the highest beam energy regardless of the mass of the PEP's. Because $\overline{E^*}/\overline{A_{CS}}$ is considerably less than this, the PEP's in coincidence with residues must travel faster, on average, than the projectile or target speeds. (4) The residue velocity spectrum contains only a single bump at the CM velocity. The lack of a double-bump indicates that in a given reaction nearly the same mass escapes in forward and backward directions due to the symmetry, which is broken only by fluctuations within the two Si ions.

All these observations point toward an explanation in which hot systems that decay into residues cannot be created with more than some limiting excitation energy per nucleon. Presumably, beyond this threshold the system splits into fragments and leaves no residue. In this letter we shall concentrate on the composite system rather than on the specifics of the dynamics. We consider a reaction between two ions of mass m_t (target) and m_p (projectile). Our data indicate that the incomplete-fusion reaction prefers few rather than many PEP fragments. Therefore, we assume that three particles, a target PEP with mass m_1, the composite system (m_2), and the projectile PEP (m_3), are produced during the initial stages of the reaction. If multiple target or projectile PEP's are emitted, this picture is still valid with an appropriate correction for mass excess. Due to Fermi motion, the PEP's m_1 and m_3 are emitted according to a distribution which is approximately gaussian.

$$f(\boldsymbol{v}_i) \sim \exp[-(\boldsymbol{v}_1 - \boldsymbol{v}_0)^2/2\sigma^2], \tag{3}$$

where $\boldsymbol{v}_0$ is close to either the CM target or projectile velocity and $\boldsymbol{v}_i$ is the velocity of mass m_i ($i = 1$ and 3). If $\boldsymbol{v}_1$ and $\boldsymbol{v}_3$ are uncorrelated, then $\boldsymbol{v}_2$, the velocity of the composite system, will not be zero in the CM frame. Conservation of momentum implies

$$\boldsymbol{v}_2 = \frac{-m_1 \boldsymbol{v}_1 - m_3 \boldsymbol{v}_3}{m_2}. \tag{4}$$

Conservation of energy implies $E_{cm} = \frac{1}{2} m_1 v_1^2 + \frac{1}{2} m_2 v_2^2 + \frac{1}{2} m_3 v_3^2 + E_1^* + E_2^* + E_3^* + Q$, which is a sum of kinetic energies $\frac{1}{2} m_i v_i^2$ and excitation energies E_i^*

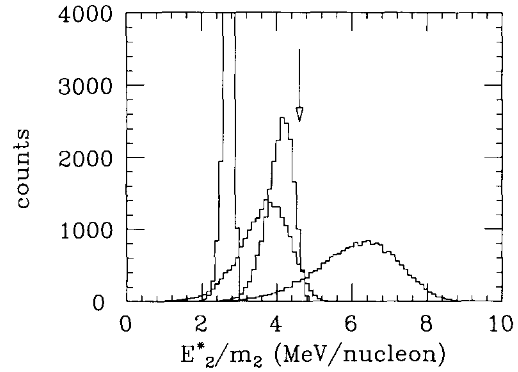

Fig. 2. Distribution of initial excitation energy per nucleon of hot systems formed by incomplete fusion. From left to right these are Si+Si at 12.4 MeV/N and 19.7 MeV/N, Ne+Al at 19.2 MeV/N [6], and Si+Si at 30.0 MeV/N. The arrow indicates the best value for $E_{\rm lim}^{\rm corr.}$. The centroids of the distributions are 2.7, 3.6, 4.1, and 6.1 MeV/N, respectively.

($i=1, ..., 3$) for each of the three masses, plus the Q-value. The consequence of this equation is that E_2^*/m_2, the initial excitation energy per nucleon of the composite system, is broadly distributed due to Fermi motion. Therefore, if there exists a limiting excitation energy for residue formation, then composite systems with energy in the upper part of the distribution E_2^*/m_2 will not show up in the residue cross section.

We used the widths extracted from our fits of α-particle PEP's to deduce σ_0 in the Goldhaber model [9]. This lets us calculate the width σ in eq. (3) and, thereby, the distributions for E_2^*/m_2 by Monte Carlo simulation. Fig. 2 shows these distributions for the different beam energies. We assumed that $E_1^* = E_3^* = 0$; that Q comes from splitting two nuclei into three fragments; that the average values of v_1 and v_3 are the CM target and projectile velocities, respectively; and that m_1 and m_3 are fixed at values determined from the data. In reality incomplete fusion produces a distribution of m_1 and m_3's. However, in the Goldhaber model the increased velocity width σ for small m's compensates somewhat for the reduced recoil; therefore, the width of E_2^*/m_2 depends only weakly on m_1 and m_3. Clearly, because both the composite system and the PEP's can absorb kinetic energy, E_2^*/m_2 peaks below the CM energy per nucleon.

Now we make the assumption that above the energy $E_{\rm lim}$, E_2^*/m_2 is too large to produce a residue. We can deduce $E_{\rm lim}$ using $\overline{E^*/A_{\rm CS}}$ from table 1. In our coincidence experiments we actually measure the average energy below $E_{\rm lim}$, which can be considerably less than $E_{\rm lim}$. In addition, the coincidence data from which $\overline{E^*/A_{\rm CS}}$ is deduced is a biased sample, since the gate on ions with $Z \geqslant 15$ eliminates as much as 50% of the residue cross section at 19.7 and 30 MeV/N. Because, in general, the residues with lower Z come from the systems with higher excitation energy, we can correct for this deficit to first order by finding the limiting energy $E_{\rm lim}$ in fig. 2 which yields the mea-

Table 2

Input data for our schematic model and the corresponding results. $Z_{\rm ER}^{\rm coinc.}$ is the charge of the heavy ions included in the coincidence data; $\epsilon_{\rm coinc.}$ is the fraction of residues included in the heavy-ion gate; f is the fraction of energies E_2^*/m_2 below $E_{\rm lim}$; $f^{\rm corr.}$ is the fraction of energies E_2^*/m_2 below $E_{\rm lim}^{\rm corr.}$ (i.e. the smaller of 100% and $f/\epsilon_{\rm coinc.}$); and $\bar{v}/v_{\rm p}$ is the average velocity of the projectile PEP's that leave a composite system with $E_2^*/m_2 < E_{\rm lim}^{\rm corr.}$, normalized by the CM beam velocity $v_{\rm p}$. All other variables are described in the text.

Reaction	$E_{\rm beam}$ (MeV/N)	$E_{\rm cm}/A$ (MeV/N)	$\overline{E^*/A_{\rm CS}}$ (MeV/N)	$Z_{\rm ER}^{\rm coinc.}$	$\epsilon_{\rm coinc.}$ (%)	σ_0 (MeV/c)
Si+Si	12.4	3.1	3.4(4)	⩾15	~80	51
Si+Si	19.7	4.9	2.8(5)	⩾15	~50	76
Si+Si	30.0	7.5	2.9(6)	⩾15	~50	87
Ne+Al[6]	19.2	4.7	4.1(3)	⩾11	~75	63

m_1 (amu)	m_2 (amu)	m_3 (amu)	Q (MeV)	$E_{\rm lim}$ (MeV/N)	f (%)	$E_{\rm lim}^{\rm corr.}$ (MeV/N)	$f^{\rm corr.}$ (%)	$\bar{v}/v_{\rm p}$
1	54	1	10	>3	100	>3	100	1.0
7	42	7	35	$3.4^{+0.7}_{-0.6}$	31	$4.0^{+\infty}_{-0.8}$	62	1.09(1)
9	38	9	30	$3.5^{+0.6}_{-0.7}$	2	$4.0^{+0.6}_{-0.8}$	4	1.29(3)
0	43	4	10	$4.6^{+\infty}_{-0.4}$	94	>4.6	100	1.0

sured average energy $\overline{E^*}/\overline{A_{CS}}$ and then by moving E_{lim} upward until the area below E_{lim} has increased by a factor of $1/\epsilon_{coinc.}$ (the reciprocal of the fraction of residue cross section sampled in the coincidence measurement), wherever possible. Table 2 lists the values of E_{lim} generated for $\overline{E^*}/\overline{A_{CS}}$ with errors calculated from $\overline{E^*}/\overline{A_{CS}} \pm \Delta\overline{E^*}/\overline{A_{CS}}$. Likewise, this table lists the limiting energy values, corrected for sample bias. Combining all results yields a limiting energy $\bar{E}^{corr.}_{lim} = 4.6 \pm 0.5$ MeV/N, where the quoted error is statistical. This number is relatively insensitive to reasonable variations of σ and Q, which add an additional error of 0.2–0.5 MeV/N. Moreover, the PEP's emitted at 30 MeV/N in coincidence with residues travel faster than the CM projectile- and target velocities (see table 2). $E^{corr.}_{lim}$ is consistent with current theoretical limits to the excitation energy of 4.5–5 MeV/N [10] deduced in a schematic phenomenological model, but lies significantly below claims of observed energies as high as 6 MeV/N [11]. Clearly the 30 MeV/N data provide the crucial evidence for limiting excitation energy. The area in fig. 2 below $\bar{E}^{corr.}_{lim}$ is 8% of the total, which agrees with the observed factor of ten reduction in the residue cross section with respect to systematics. For the other beam energies we see that the distributions E^*_2/m_2 lie, for the most part, below our estimate of $\bar{E}^{corr.}_{lim}$, which agrees with the fact that the cross sections fit into the systematics in this case.

The data on Si+Si show tantalizing evidence of a limiting energy for residue formation consistent with some theoretical estimates, but well below the 8 MeV/N binding energy in nuclei. All of the features of our data can be reasonably explained in a schematic model that takes into account the distribution of velocities of the PEP's. Initial calculations [12] with a more sophisticated Monte Carlo program, which includes experimental mass and velocity distributions as well as the statistical decay of the composite system, are in general agreement with the results presented above.

We would like to thank the staffs at KVI and SARA for providing us with excellent heavy-ion beams. This work has been supported by the Stichting voor Fundamenteel Onderzoek der Materie (FOM) with financial support of the Stichting Nederlands Wetenschappelijk Onderzoek (NWO) and by the National Science Foundation.

References

[1] R.J. Meijer, A. van den Brink, E.A. Bakkum, P. Decowski, K.A. Griffioen and R. Kamermans, Nucl. Instrum. Methods A 256 (1987) 521.
[2] R.J. Meijer, G.J. van Nieuwenhuizen, A. van den Brink, P. Decowski, K.A. Griffioen and R. Kamermans, Nucl. Instrum. Methods A 264 (1988) 285.
[3] R.J. Meijer, P. Box, P. Decowski, K.A. Griffioen, R. Kamermans, G.J. van Nieuwenhuizen, H.W. Wilschut, A. Giorni, C. Morand, A. Demeyer and D. Guinet, Proc. XXVII Winter Meeting on Nuclear physics, ed. I. Iori (Bormio, Italy, January 1989) p. 203.
[4] R.J. Meijer, Thesis, University of Utrecht (1989).
[5] R.J. Meijer, P. Box, P. Decowski, K.A. Griffioen, R. Kamermans, G.J. van Nieuwenhuizen, H.W. Wilschut, A. Giorni, C. Morand, A. Demeyer and D. Guinet, in preparation for Phys. Rev. C.
[6] K.A. Griffioen, E.A. Bakkum, P. Decowski, R.J. Meijer and R. Kamermans, Phys. Rev. C 37 (1988) 2502.
[7] K.A. Griffioen, B.J. Gluckman, R.J. Meijer, P. Decowski and R. Kamermans, Phys. Rev. C 40 (1989) 1647.
[8] M.F. Vineyard et al., Physics Division Annual Review, 1 April 1988–31 March 1989 (Argonne National Laboratory, Argonne, IL) pp. 34–35;
G. Rosner et al., Bull. Am. Phys. Soc. 28 (1983) 670;
S.B. DiCenzo et al., Phys. Rev. C 23 (1981) 2561.
[9] A.S. Goldhaber, Phys. Lett. B 53 (1974) 306.
[10] C. Cerruti, J. Desbois, R. Boisgard, C. Ngô, J.Natowitz and J. Nemeth, Nucl. Phys. A 476 (1988) 74.
[11] M. Gonin, J.P. Coffin, G. Guillaume, F. Jundt, P. Wagner, P. Fintz, B. Heusch, A. Malki, A. Fahli, S. Kox, F. Merchez and J. Mistretta, Phys. Rev. C 38 (1988) 135.
[12] R.J. Meijer, private communication.